REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
25-05-2012	Final Report	15-Feb-2008 - 14-Feb-2013

4. TITLE AND SUBTITLE	
Final Technical Report	5a. CONTRACT NUMBER W911NF-08-1-0058
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 7720T2
6. AUTHORS Alexander L. Gaeta	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Cornell University Office of Sponsored Programs Cornell University Ithaca, NY 14853 -2801	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 54331-EL-DRP.10

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

During this project, we found that two-photon and free-carrier absorption are primary facilitators of crosstalk in silicon nanowaveguides. We experimentally demonstrated four-wave-mixing-based continuous wavelength conversion of optical differential-phase-shift-keyed signals with large wavelength conversion ranges and simultaneous wavelength conversion of dual-wavelength channels with mixed modulation formats in 1.1-cm-long dispersion-engineered silicon waveguides. We demonstrated broadband continuous wavelength conversion based

15. SUBJECT TERMS

four-wave mixing, nanophotonics, nanowaveguides, nonlinear optical devices, nonlinear optics, optical crosstalk, optical fibers, optical signal processing, optical wavelength conversion, probes, silicon

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Alexander Gaeta
UU	UU	UU	UU		19b. TELEPHONE NUMBER 607-255-9983

Report Title

Final Technical Report

ABSTRACT

During this project, we found that two-photon and free-carrier absorption are primary facilitators of crosstalk in silicon nanowaveguides. We experimentally demonstrated four-wave-mixing-based continuous wavelength conversion of optical differential-phase-shift-keyed signals with large wavelength conversion ranges and simultaneous wavelength conversion of dual-wavelength channels with mixed modulation formats in 1.1-cm-long dispersion-engineered silicon waveguides. We demonstrated broadband continuous wavelength conversion based on four-wave mixing in silicon waveguides, operating with data rates to 40Gb/s, validating signal integrity using bit-error-rate measurements. We demonstrated a scalable, energy-efficient, and pragmatic method for high-bandwidth wavelength multicasting using FWM in silicon photonic nanowires. We demonstrated reduction of the free-carrier lifetime in a silicon nanowaveguide from 3ns to 12.2ps by applying a reverse bias across an integrated p-i-n diode. We demonstrated ultrabroad-bandwidth low-power frequency conversion of continuous-wave light in a dispersion engineered silicon nanowaveguide via four-wave mixing. We demonstrated all-optical continuously tunable delay line based on parametric mixing with a total delay range of 7.34us. We demonstrated a monolithically integrated CMOS-compatible source using an optical parametric oscillator based on a silicon nitride ring resonator on silicon. Lastly, we demonstrated continuously tunable optical delays as large as 1.1us range for 10Gb/s NRZ optical signals based on four-wave mixing process in silicon waveguide.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/05/23 1! 9	Yitang Dai, Xianpei Chen, Yoshitomo Okawachi, Amy C. Turner-Foster, Mark A. Foster, Michal Lipson, Alexander L. Gaeta, Chris Xu. 1 us tunable delay using parametric mixing and optical phase conjugation in Si waveguides, Optics Express, (04 2009): 0. doi: 10.1364/OE.17.007004
2012/05/23 1! 8	Jacob S. Levy, Alexander Gondarenko, Mark A. Foster, Amy C. Turner-Foster, Alexander L. Gaeta, Michal Lipson. CMOS-compatible multiple-wavelength oscillator for on-chip optical interconnects, Nature Photonics, (12 2009): 0. doi: 10.1038/nphoton.2009.259
2012/05/23 1! 7	Yitang Dai, Yoshitomo Okawachi, Amy C. Turner-Foster, Michal Lipson, Alexander L. Gaeta, Chris Xu. Ultralong continuously tunable parametric delays via a cascading discrete stage, Optics Express, (12 2009): 0. doi: 10.1364/OE.18.000333
2012/05/23 1! 6	Amy C. Turner-Foster, Mark A. Foster, Reza Salem, Alexander L. Gaeta, Michal Lipson. Frequency conversion over two-thirds of an octave in silicon nanowaveguides, Optics Express, (01 2010): 0. doi: 10.1364/OE.18.001904
2012/05/23 1! 5	Amy C. Turner-Foster, Mark A. Foster, Jacob S. Levy, Carl B. Poitras, Reza Salem, Alexander L. Gaeta, Michal Lipson. Ultrashort free-carrier lifetime in low-loss silicon nanowaveguides, Optics Express, (02 2010): 0. doi: 10.1364/OE.18.003582
2012/05/23 1! 4	Aleksandr Biberman, Benjamin G. Lee, Amy C. Turner-Foster, Mark A. Foster, Michal Lipson, Alexander L. Gaeta, Keren Bergman. Wavelength multicasting in silicon photonic nanowires, Optics Express, (08 2010): 0. doi: 10.1364/OE.18.018047
2012/05/23 1! 3	Noam Ophir, Johnnie Chan, Kishore Padmaraju, Aleksandr Biberman, Amy C. Foster, Mark A. Foster, Michal Lipson, Alexander L. Gaeta, Keren Bergman. Continuous Wavelength Conversion of 40-Gb/s Data Over 100 nm Using a Dispersion-Engineered Silicon Waveguide, IEEE Photonics Technology Letters, (01 2011): 0. doi: 10.1109/LPT.2010.2090138
2012/05/23 1! 2	Noam Ophir, Lin Xu, Michael Menard, Ryan Kin Wah Lau, Amy C. Turner-Foster, Mark A. Foster, Michal Lipson, Alexander L. Gaeta, Keren Bergman. Simultaneous wavelength conversion of ASK and DPSK signals based on four-wave-mixing in dispersion engineered silicon waveguides, Optics Express, (06 2011): 0. doi: 10.1364/OE.19.012172
2012/05/23 1! 1	Yoshitomo Okawachi, Onur Kuzucu, Mark A. Foster, Reza Salem, Amy C. Turner-Foster, Aleksandr Biberman, Noam Ophir, Keren Bergman, Michal Lipson, Alexander L. Gaeta. Characterization of Nonlinear Optical Crosstalk in Silicon Nanowaveguides, IEEE Photonics Technology Letters, (02 2012): 0. doi: 10.1109/LPT.2011.2177080

TOTAL: **9**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Alessandro Farsi	0.11	
Andrea Johnson	0.02	
Ryan Lau	0.18	
Kriti Charan	0.04	
Xianpai Chen	0.37	
Demirhan Kobat	0.11	
FTE Equivalent:	**0.83**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Mark Foster	0.52
Oktay Onur Kuzucu	0.29
Pablo Londero	0.48
Yoshitomo Okawachi	0.37
Aaron Slepkov	0.42
Yitang Dai	0.22
Ke Wang	0.19
Zinan Wang	0.31
FTE Equivalent:	**2.80**
Total Number:	**8**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Alexander L. Gaeta	0.07	No
Chris Xu	0.05	No
FTE Equivalent:	**0.12**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Final Technical Report, “Parametric Ultra-High Bandwidth Silicon-Based Devices and Systems”

During the course of this project, we accomplished the following:

We investigated optical crosstalk on a signal in a silicon nanowaveguide due to the presence of another signal by direct radio frequency crosstalk level measurements in a pump-probe configuration and by bit-error-rate-based characterization. We quantified this degradation as a function of the modulation frequency and power of the auxiliary signal. Our results indicate that two-photon and free-carrier absorption are primary facilitators of crosstalk in silicon nanowaveguides.

We experimentally demonstrated four-wave-mixing (FWM)-based continuous wavelength conversion of optical differential-phase-shift-keyed (DPSK) signals with large wavelength conversion ranges as well as simultaneous wavelength conversion of dual-wavelength channels with mixed modulation formats in 1.1-cm-long dispersion-engineered silicon waveguides. We first validated up to 100-nm wavelength conversion range for 10-Gb/s DPSK signals, showcasing the capability to perform phase-preserving operations at high bit rates in chip-scale devices over wide conversion ranges. We further validated the wavelength conversion of dual-wavelength channels modulated with 10-Gb/s packetized phase-shift-keyed (PSK) and amplitude-shift-keyed (ASK) signals; demonstrated simultaneous operation on multiple channels with mixed formats in chip-scale devices. For both configurations, we measured the spectral and temporal responses and evaluated the performance using bit-error-rate (BER) measurements.

We demonstrated broadband continuous wavelength conversion based on four-wave mixing in silicon waveguides, operating with data rates up to 40 Gb/s, validating signal integrity using bit-error-rate measurements. The dispersion-engineered silicon waveguide provides broad phase-matching bandwidth, enabling complete wavelength-conversion coverage of the S -, C-, and L-bands of the International Telecommunication Union (ITU) grid. We experimentally showed this with wavelength conversion of high-speed data exceeding 100 nm, and characterized the resulting power penalty induced by the wavelength conversion process. We then validated the bit-rate transparency of the all-optical process by scaling the data rate from 5 Gb/s up to 40 Gb/s at the 100-nm wavelength conversion configuration, showing consistent low power penalties, validating the robustness of the four-wave mixing process in the silicon platform for all-optical processing.

We demonstrated a scalable, energy-efficient, and pragmatic method for high-bandwidth wavelength multicasting using FWM in silicon photonic nanowires. We experimentally validated up to a sixteen-way multicast of 40-Gb/s NRZ data using spectral and temporal responses, and evaluated the resulting data integrity degradation using BER measurements and power penalty performance metrics. We further examined the impact of this wavelength multicasting scalability on conversion efficiency. Finally, we experimentally evaluated up to a three-way multicast of 160-Gb/s pulsed-RZ data using spectral and temporal responses, representing the first on-chip wavelength multicasting of pulsed-RZ data.

We demonstrated reduction of the free-carrier lifetime in a silicon nanowaveguide from 3 ns to 12.2 ps by applying a reverse bias across an integrated *p-i-n* diode. This observation represents the shortest free-carrier lifetime demonstrated to date in silicon waveguides. Importantly, the presence of the *p-i-n* structure does not measurably increase the propagation loss of the waveguide. We derived a figure of merit demonstrating equal dependency of the nonlinear phase shift on free-carrier lifetime and linear propagation loss.

We demonstrated ultrabroad-bandwidth low-power frequency conversion of continuous-wave light in a dispersion engineered silicon nanowaveguide via four-wave mixing. Our process produces continuously tunable four-wave mixing wavelength conversion over two-thirds of an octave from 1241-nm to 2078-nm wavelength light with a pump wavelength in the telecommunications C-band.

We reported experimental demonstration of an all-optical continuously tunable delay line based on parametric mixing with a total delay range of 7.34 us. The bit-error rate performance of the delay line was characterized for a 10-Gb/s NRZ data channel. This result is enabled by cascading a discrete delay line that consists of 16 wavelength-dependent delays and a continuously tunable delay stage. Four wavelength conversion stages based on four-wave mixing in silicon waveguides were performed in order to achieve wavelength-preserving operation. The wavelength-optimized optical phase conjugation scheme employed in the delay line is capable of minimizing the residual dispersion for the entire tuning range.

A monolithically integrated CMOS-compatible source was demonstrated using an optical parametric oscillator based on a silicon nitride ring resonator on silicon. Generating more than 100 wavelengths simultaneously and operating at powers below 50 mW, scientists say that it may form the basis of an on-chip high-bandwidth optical network.

We demonstrated continuously tunable optical delays as large as 1.1 us range for 10 Gb/s NRZ optical signals based on four-wave mixing (FWM) process in silicon waveguide. The large delay range is made possible by a novel wavelength-optimized optical phase conjugation scheme, which allows for tunable dispersion compensation to minimize the residual group-velocity dispersion (GVD) for the entire tuning range.